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SHARPENING pH CONTROL

Plagued by Limit Cycling or Sluggish Response? Match the Characterizer to the Process to Optimize Gain and Stability.

By Greg Shinskey

Most pH titration curves are very nonlinear, and pH controllers normally have their setpoint at the neutral point, in the steepest region of the curve. As a result, steady-state gain-the slope of the curve at setpoint-is very high, requiring a low controller gain for stability. If the proportional gain of the controller is not set low enough for stability, the loop will limit cycle at an amplitude (pH, where the average slope of the curve (DpH/Dm) produces a loop gain of unity (Dm being the swing in controller output).

Limit cycling is undesirable, especially if the controller is manipulating sequenced acidic and basic reagents, as it consumes those reagents excessively. While the cycle may be attenuated by sufficient downstream capacity, there is no guarantee that the final pH will equal the setpoint of the controller. If the titration curve is not perfectly symmetrical, the setpoint and final pH will not agree, and any gain change in the loop will affect their difference. Therefore, the pH controller should be tuned for stability in the worst case: the highest loop gain likely to be encountered.

CHARACTERIZER CHOICES

When using a linear controller, the loop gain tends to decrease as the deviation from setpoint increases, retarding the corrective action of the controller in response to a load change. Response can be improved by adding a characterizer at the input of the controller to linearize the loop and thereby keep its gain more uniform as pH deviates from setpoint. Many types of characterizers are available, with three common choices shown in Figure 1.

The crudest of the characterizers consists of three straight-line segments forming a zone of low gain around the setpoint, flanked by zones of normal gain (unity slope) on either side.

A smoother characteristic is obtained using a parabolic function whose slope gradually increases from zero at zero deviation to unity as deviations approach ±50%. Labeled e2 in Figure 1, it is commonly called the error-squared function but is actually the deviation or error e multiplied by its absolute value.

The ideal characterizer would be one that matches the titration curve exactly, because this would linearize the loop across the entire pH scale. The issue to be resolved here is whether a simpler characterizer can be effective with only an approximate match to the titration curve.
To make this determination, we simulated a stirred tank with a residence time of 20 minutes, in which a strong acid is neutralized by a strong base. The titration c urve used in the simulation is representative of industrial wastewater, consisting of 10-3 N hydrochloric acid and 10-5 N carbon dioxide, the latter associated with water hardness (the equivalent of 0.25 ppm calcium carbonate).

The titration curve for this mixture is identical to that of the matched characterizer, but with the axes exchanged-pH being the output rather than the input of the function. The slope of the curve at setpoint (pH 7) is 75 in terms of percent pH on the scale of 2-12 against percent caustic flow where the caustic valve is sized for twice the initial load.

RESPONSES UNDER PID CONTROL

Step changes in acid flow from an initial value of 50 to 40% were introduced into the simulation to compare the response of the pH loop under PID control with and without the above characterizers. In all the tests, the controller was tuned for well-damped response at setpoint, where the gain of the titration curve is maximum.

The first response to be examined is of the pH loop with no characterizer; that is, under linear PID control (Figure 2). Loop gain is so low outside the range of pH 6-8 that recovery is very slow. During this time, the integrated error continues to accumulate or wind up, resulting in a large overshoot. Not until the deviation is quite small does the response appear normal.

If the process were linear, the period under PID control would be on the order of six minutes, and the integral and derivative times of the controller are set accordingly, at 2.5 and 1.0 min. respectively. This rate of integration is then much too fast for the observed large-amplitude period of nearly 30 min. For the linear controller, the proportional band was optimized at 870%. The above integral and derivative settings were found to be optimum regardless of characterization.

The three-zone characterizer has two adjustments that require tuning: the width of the low-gain central zone, and the gain within it. To make this characterizer effective, the central zone requires a very low (but not zero) gain-here 0.05 was used. The width of the central zone should approach the knees of the pH curve-here it was set at ±1.5 pH.

The gain change is quite sharp when the deviation crosses zones, which produces the earliest recovery of all the curves in Figure 2. While the peak pH value for the three-zone response curve barely exceeds the low-gain zone at pH 8.5, the input signal to the characterizer is actually much greater than the deviation; including the derivative of pH as well as its deviation.

Most of the first two cycles of the three-zone response curve therefore are acted upon by much higher than the minimum gain and so are lightly damped; by contrast, the tail of the curve lies completely within the low-gain zone where the damping is high. The proportional band of the controller was set at 44%, which, when divided by the 0.05 gain of the central zone, results in the same loop gain at setpoint as with the linear controller.

The parabolic, or e2, characterizer is available in many controllers as the error-squared algorithm. The proportional gain of the controller is made to vary directly with the absolute value of the error or deviation, producing the e2 function shown in Figure 1. Because the proportional gain of the controller is zero at zero deviation, the loop tends to control with an offset. This can be corrected by placing a low limit or bias on the gain to keep it at or above a small number such as 0.05; but this was not done in the simulation, resulting in very little correction for small deviations.

The gain of this characterizer is not as high at large deviations as that of the three-zone function. The result is slower recovery and more overshoot, similar in appearance to the response produced by the linear controller, but much faster and tighter. The advantage of the e2 characterizer is that it requires no tuning. The proportional band of its controller was optimized at 60%.

The last characterizer to be tested was matched to the titration curve-an exact inverse-so that the loop is linearized. While it also does not require tuning, the matched characterizer is much more complex than the others. The one used in the simulation consisted of 200 points with linear interpolation between them, although 15-20 straight-line segments would probably suffice.

To implement, the measured pH (along with its derivative) and the setpoint are independently passed through the same characterizer. The two characterized outputs are then subtracted and their difference acted on by the proportional and integral functions of the controller. The matched characterizer produces the best of the four response curves, exhibiting fast recovery, uniform damping, and minimal overshoot. The optimum proportional band for its controller was only 10%.

ROBUSTNESS UNDER PID CONTROL

To verify that stability was independent of step size, 20% and 5% step reductions in acid flow were also introduced into the simulation, throughout which all loops remained stable. For the linear controller, integrated error varied directly with step size as expected. All of the characterized controllers were more effective in response to larger upsets, however, with integrated error typically increasing only 15% following doubling of the step size from 10 to 20%. As step size approaches zero, the responses of all the loops become identical.

However, relatively small increases in gain were found to destabilize some of the loops under PID control. When the proportional band of the controller using the matched characterizer was reduced from 10 to 8%, (equivalent to only a 25% increase in process gain), a step in load produced an expanding cycle that soon saturated the controller, ending in a limit cycle from 5-9 pH. Stability could not be restored without increasing the proportional band to 50%-five times its optimum value! (Forget about trying to restore stability manually-it is impossible to return pH to setpoint by hand in a high-gain loop such as this.)

The three-zone controller also developed a limit cycle following the step in load after its proportional band was lowered from 44 to 35% (again equivalent to a 25% increase in process gain) or the width of its central zone was reduced from ±1.5 to ±1.3 pH. The proportional band then had to be raised to 120% to restore stability, about a four-fold increase.

The error-squared controller was more robust: decreasing the proportional band from 60 to 40% (equivalent to a 50% increase in process gain) started the cycle, but returning it to its optimum value of 60% was sufficient to restore stability (after a few cycles).

RESPONSE UNDER PI CONTROL

The fragility described above seemed to be associated with derivative action, as the behavior did not appear under PI control. However, performance decreases substantially when derivative action is removed, as the time response of the loop is nearly doubled. The optimum integral time of the controllers increased from 2.5 to 6 min., with an associated increase in integrated error.

Figure 3 describes the load responses for the four PI loops, which fall in the same relative order as in Figure 2. The most noticeable difference between the two figures is in the response of the three-zone controller. Now only the tip of its first peak exceeds the low-gain zone-the balance of the curve lies entirely within it, resulting in overshoots similar to those produced by the linear controller.

The matched characterizer has the best response again, but the e2 characterizer is remarkably effective for its simplicity. Its tendency for offset, evident here, is not usually considered a problem for wastewater neutralization, where specifications may be as broad as pH 6-9. And its superior robustness with derivative action is an important factor in its favor.

WHEN SELF-TUNING IS NEEDED

Robustness is a prime consideration in wastewater pH control because the composition of the stream is subject to change. Addition or loss of buffers such as cleaning agents, metal ions, and organic acids and bases can profoundly affect the shape of the titration curve. To ensure stability at all times, the characterizer and controller must be tuned for worst-case conditions: the steepest titration curve likely to be encountered. Loop gain then will be lower for all other cases, with resulting slow recovery from disturbances.

Where variable buffering is expected, the best solution is a self-tuning controller-one that recognizes a cycling situation and increases its proportional band as needed to restore stability. If derivative action is used, the three-zone and matched characterizers will make this difficult by requiring a four or five-fold increase in proportional band to break a limit cycle, leaving the band too wide for effective control at this point. The self-tuner then would have to reduce the band by three or four fold again to restore performance. It is possible that a self-tuner in this environment would itself limit cycle between controller settings that are unstable and those that are ineffective.

RECOMMENDATIONS

The use of derivative action is usually conditioned on the presence of noise in the measured variable: high frequencies amplified by derivative gain cause too much activity on the controller output, which wears out actuators without producing any benefit. But in the absence of noise, particularly when applied to lag-dominant processes such as stirred tanks, the use of derivative action can double controller performance in terms of integrated error, and is therefore recommended.

However, in the context of this study on characterized pH control, robustness considerations limit its use to the error-squared controller. And the e2 PID controller definitely outperforms the matched characterizer with a PI controller.

If, due to noise considerations, derivative action cannot be used, a matched characterizer is the best choice. For processes having an asymmetrical titration curve, or where the setpoint is not positioned at its center or is subject to change, a matched characterizer has definite advantages. But it is also more complex, and can be configured to match only a single titration curve.

The three-zone characterizer has the advantage of limiting the maximum excursions in pH most effectively, which may be important in some situations where downstream capacity is not available to attenuate swings. But it does require setting of two parameters.

When titration curves are so variable that self-tuning is required, the best choice of characterizer seems to be the e2, as it does not require matching or tuning, and can exit a limit cycle at the optimum proportional band, even with the derivative mode active.

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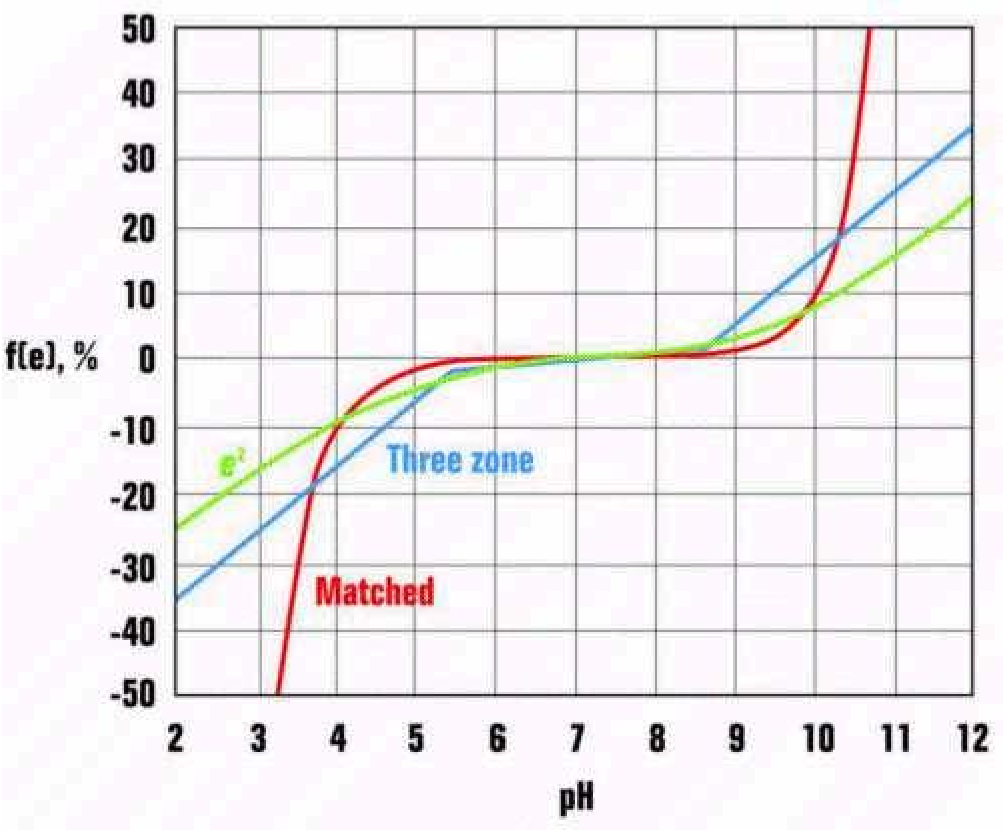
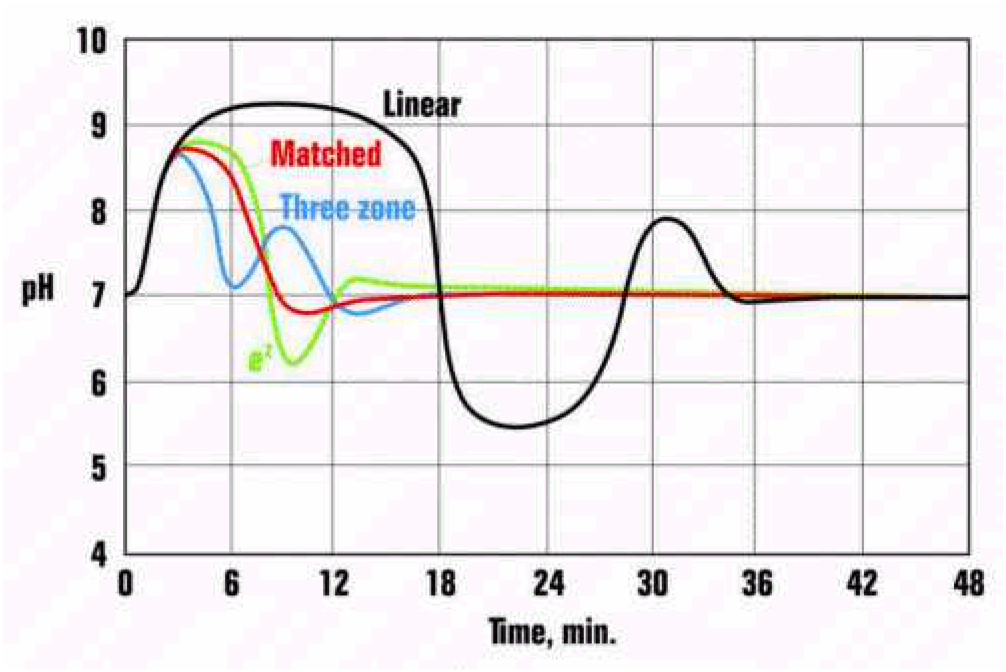
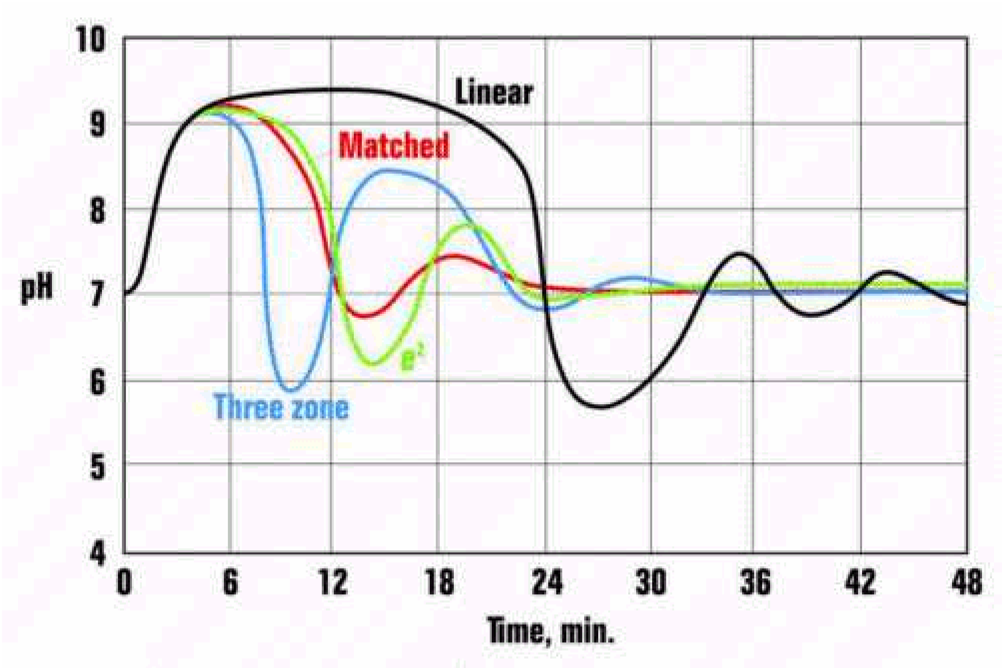
Figure 1
The ideal characterizer matches the titration curve exactly,
linearizing the loop across the entire pH scale.
But a simpler characterizer can be effective.





Step load response under PID control is best with the matched characterizer, though any characterizer is a significant improvement over linear PID control.



Under PI control, the matched characterizer is best.
but if noise is not a problem, the e2 pid controller is better.